NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3256

EXPERIMENTAL INVESTIGATION OF TEMPERATURE RECOVERY FACTORS ON A 10° CONE AT ANGLE OF ATTACK AT A MACH NUMBER OF 3.12

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SUMMARY

Temperature recovery factors on a thin-walled, metal, 10° included angle cone were obtained at a Mach number of 3.12 over a range of angles of attack from 0° to 10° and for Reynolds numbers per foot from 1.5×10^{6} to 8×10^{6}. Over the Reynolds number range investigated, an increase in angle of attack increased the equilibrium surface temperatures in the laminar and turbulent boundary-layer regions. The equilibrium surface temperatures in regions of probable cross-flow separation were in the same range as those obtained for fully turbulent flow.

For the windward surface of the model, local recovery factors in the fully laminar and turbulent regions were not significantly affected by changes in angle of attack. At all angles of attack, increasing the free-stream Reynolds number moved the transition region upstream. For a given angle of attack, the transition region on the leeward surface is substantially upstream of that on the windward surface.

INTRODUCTION

Calculation of the cooling requirements for supersonic missiles depends on a knowledge of the type of boundary layer (i.e., laminar, transitional, or turbulent), the temperature recovery factors, and the rate of heat transfer to be expected on the missile surfaces.

Experimental heat-transfer characteristics on bodies of revolution at zero angle of attack have been obtained for both laminar and turbulent boundary layers for large ranges of Mach numbers and Reynolds numbers, and the agreement with theoretical predictions is generally good (see, for example, refs. 1 and 2). The effects of angle of attack, however, have not been extensively investigated. Only a brief mention of these effects is currently available in the literature (ref. 3).

An investigation of supersonic heat transfer for bodies of revolution at various angles of attack has therefore been initiated at the NACA Lewis laboratory. This note is a presentation of the experimentally determined recovery factors for a 10° included angle cone at angles of attack from zero to 10° and for Reynolds numbers per foot from 1.5×10^{6} to 8×10^{6}.

APPARATUS AND DATA REDUCTION

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This investigation was conducted in the NACA Lewis 1- by 1-foot supersonic wind tunnel, which operates at a Mach number of 3.12. Inlet pressures can be varied from 6 to 52 pounds per square inch absolute at a stagnation temperature of approximately 50° F. These conditions yield a free-stream Reynolds number per foot variation of approximately 1×10^{6} to 8×10^{6}. The corresponding measured axial turbulence intensity in the test section for this Reynolds number range is approximately 3.5 to 1.0 percent (ref. 4). Throughout the investigation the quantity of water vapor present was kept at a value sufficiently low so that the effects of condensation were negligible.

A sketch of the model investigated with pertinent dimensions is presented in figure 1. The 10° included angle cone was fabricated from stainless steel with a wall thickness of 0.032 inch and was finished to a maximum roughness less than 15 microinches.

Axial temperature distributions for the model were determined from one row of 33 stainless-steel - constantan thermocouples. Meridional temperature distributions were obtained for five meridian angles: $\theta = 0^{\circ}$, 45°, 90°, 135°, and 180° (fig. 1). The thermocouple voltages for the model and those indicating the total temperature upstream of the wind-tunnel nozzle were read on a self-balancing potentiometer. A calibration of the thermocouples and potentiometer used to obtain the temperatures showed the measuring system to have a maximum error of $\pm 0.25^{\circ}$ F. Because of slight variations in the total temperature during a temperature survey, the reproduction of the temperatures was probably of the order of $\pm 0.5^{\circ}$ F.

Equilibrium-temperature data are usually presented in terms of local recovery factor, defined by

$$r = \frac{T_s - t_1}{T_0 - t_1} \tag{1}$$

where

T_s equilibrium surface temperature

t_1 local static temperature at edge of boundary layer

T_0 total temperature

This recovery factor has the disadvantage that local conditions at the edge of the boundary layer must be known. In separated cross-flow regions, which are generally encountered with bodies at angle of attack, neither the edge of the boundary layer nor the local stream conditions are easily defined. Therefore, a recovery factor based on free-stream conditions upstream of the body will be used, as well as the local recovery factor where the latter has special significance. The free-stream recovery factor is defined as

$$\eta = \frac{T_s - t_0}{T_0 - t_0} \tag{2}$$

where t_0 is the free-stream static temperature. This factor is directly proportional to the equilibrium surface temperature.

RESULTS AND DISCUSSION

The axial free-stream recovery-factor distributions for Reynolds numbers per foot of 1.5, 4.7, and 8.0×10^6, angles of attack of zero and 10°, and three angular positions are presented in figure 2. Inasmuch as a rise in recovery factor from an approximate laminar value to an approximate turbulent value is generally associated with transition, figure 2 illustrates the forward movement of the transition region with increasing Reynolds number.

Included in figure 2(a) for comparison with the experimental data are two theoretical values of the flat-plate recovery factor: the square root (laminar), and the cube root (turbulent) of the Prandtl number. The Prandtl number chosen was 0.720 corresponding to an average wall temperature of approximately 0° F. Although the experimental data are based on free-stream conditions, this comparison is valid because the free-stream recovery factor for this model at zero angle of attack is at most 0.004 greater than the local recovery factor. The experimental laminar free-stream recovery factors for zero angle of attack lie between 0.846 and 0.854 while those for the turbulent boundary layer lie between 0.876 and 0.882 (fig. 2(a)). The recovery factor predicted by the theory of reference 5 using the average of the wall and local static temperature as a reference temperature and a $1/7^{th}$ power velocity profile is 0.885. This value is in closer agreement with the turbulent data presented in figure 2(a) than the cube root of the Prandtl number.

The effect of angle of attack on the free-stream recovery factors is illustrated in figure 3 for three Reynolds numbers and three angular positions. For all Reynolds numbers, the effects of increasing the angle of attack is to increase the free-stream recovery factors in the laminar and turbulent regions. For the angles of attack investigated, no definite trend was established for regions of probable cross-flow separation. Cross-flow separation is generally expected to occur on the leeward surface towards the rear of the model. The recovery factors obtained in this region were found to be in the same range as those obtained for fully turbulent flow.

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For the higher Reynolds numbers and a meridian angle of zero (figs. 3(b) and (c)), increasing the angle of attack moved the transition region towards the base of the model. This result is attributed to the thinning of the laminar boundary layer as described in references 6 and 7 and a consequent increase in stability. For a meridian angle of 180°, other investigators (see ref. 6, for example) have shown that the transition point moves forward as the angle of attack is increased. The recovery-factor distributions for a Reynolds number of 1.5×10^{6} per foot agree with this latter trend; however, for the higher Reynolds numbers the transition region is so close to the tip that no trend can be established.

If the recovery factors are based on local conditions (eq. (1)) rather than on free-stream conditions (eq. (2)), practically no angle of attack effects for the laminar and turbulent regions (as distinct from the transition region) are observed. This is illustrated in figure 4 where the recovery factors for zero meridian angle and Reynolds numbers per foot of 1.5×10^{6} and 8.0×10^{6} have been referenced to the local conditions (eq. (1)) which were obtained from an exact cone theory (refs. 8 and 9). Also included in figure 4 for comparison are the theoretical flat-plate values of recovery factor.

The free-stream recovery-factor contours presented in figure 5 give an over-all picture of the effect of angle of attack at a constant Reynolds number per foot of 8.0×10^{6}. The locus of the maximum temperatures is presumed to lie within the zone of transition from laminar to turbulent flow.

As a point of interest, contour plots of recovery factor based on theoretical local Mach number have also been plotted in figure 6 even though these local theoretical Mach numbers are not valid in the separated cross-flow region. A comparison of figures 5 and 6 shows the two sets of contours to be generally similar. The local contours indicate that for meridian angles from 0° to 90° in the turbulent region the effect of angle of attack is small as was mentioned previously in the discussion of figure 4. The relatively high recovery factors on the leeward side of the model may be due merely to the discrepancy between theoretical and actual local Mach number in the region of cross-flow separation.

CONCLUSIONS

Based on an investigation of recovery factors for a 10° included angle cone at angle of attack and over a Reynolds number range from 1.5×10^{6} to 8×10^{6}, the following conclusions have been reached:

1. For the Reynolds number range investigated, increasing the angle of attack resulted in an increase in the equilibrium surface temperature
3294 in the laminar and turbulent flow regions.

2. In regions of probable cross-flow separation, the recovery factors were in the same range as those obtained for fully turbulent flow.

3. Recovery factors based on local conditions in the fully laminar and turbulent regions on the windward half of the body were not signiicantly affected by changes in angle of attack.

4. At all angles of attack, an increasing Reynolds number caused a general upstream movement of the transition region.

5. At angle of attack the transition region is substantially farther upstream on the leeward surface than that on the windward surface.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 11, 1954

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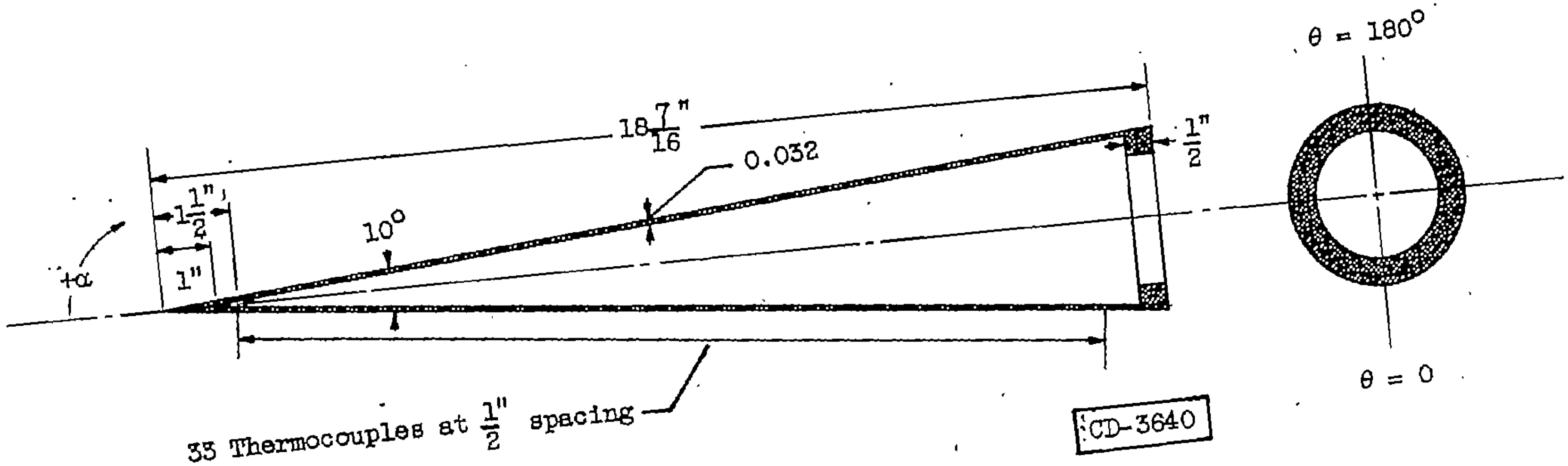
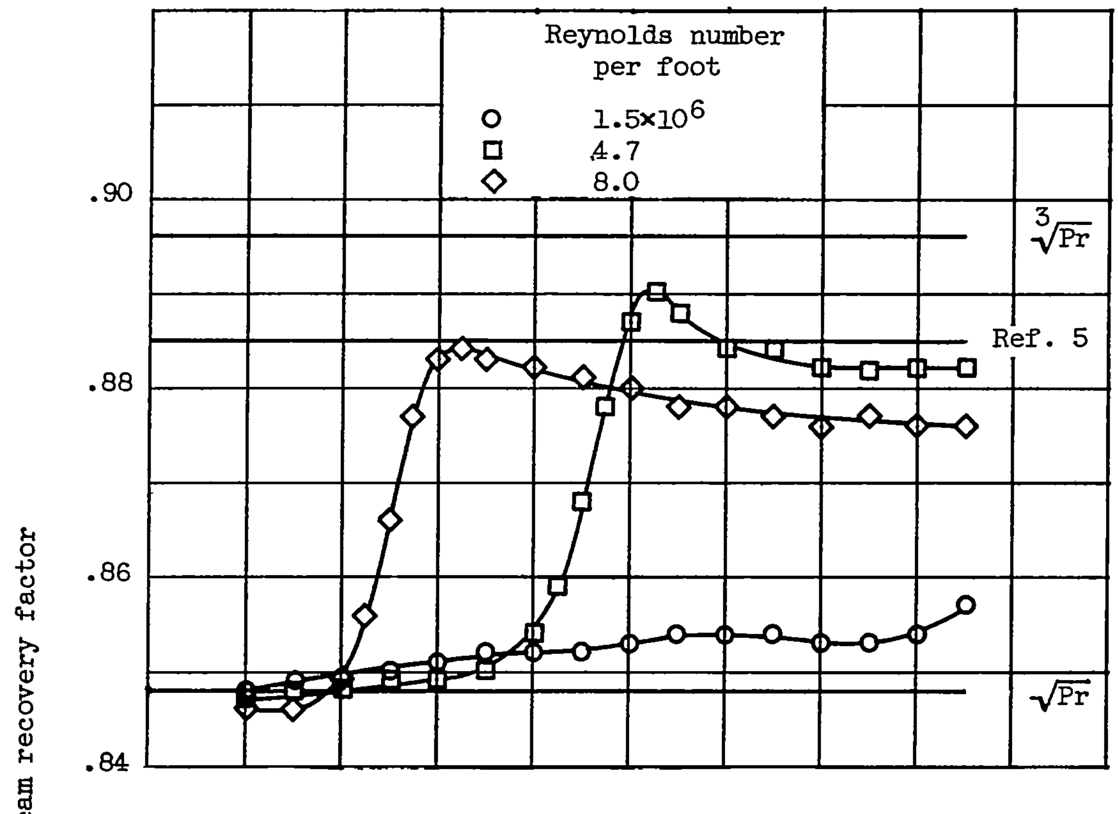
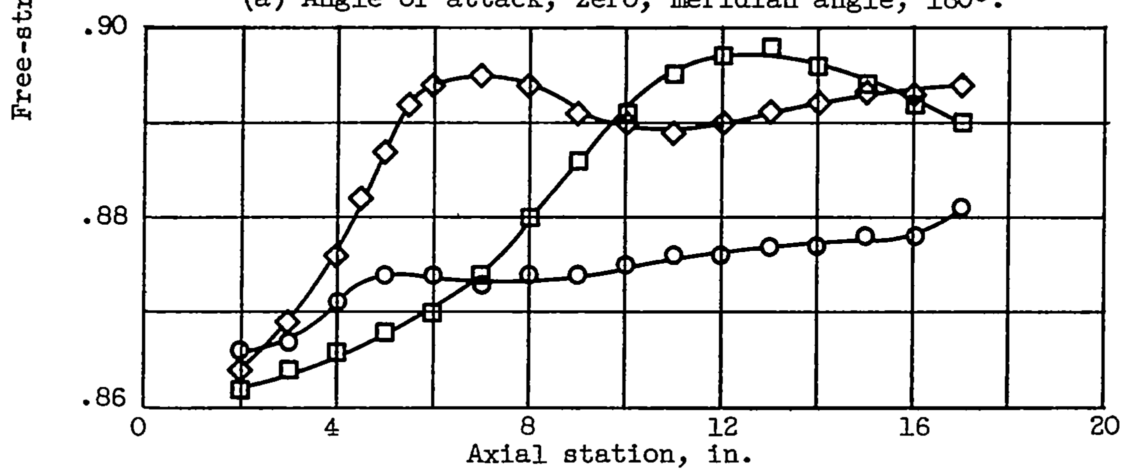


Figure 1. - Cone geometry and thermocouple locations.

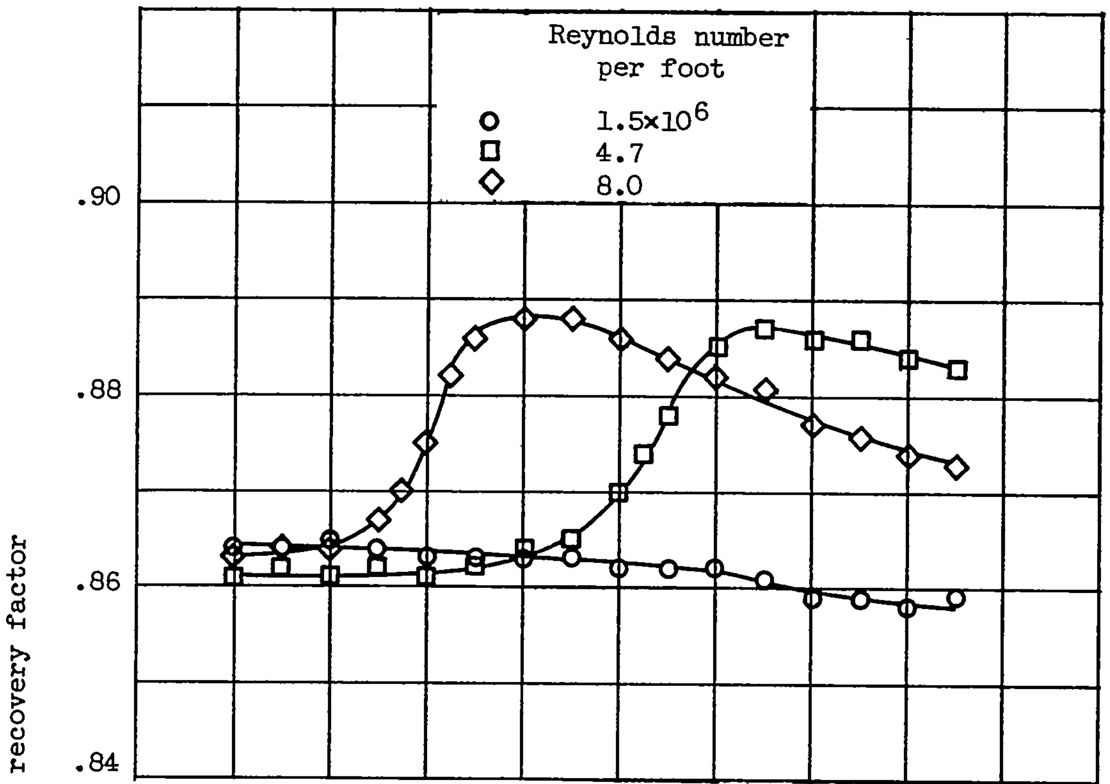


(a) Angle of attack, zero; meridian angle, 180°.

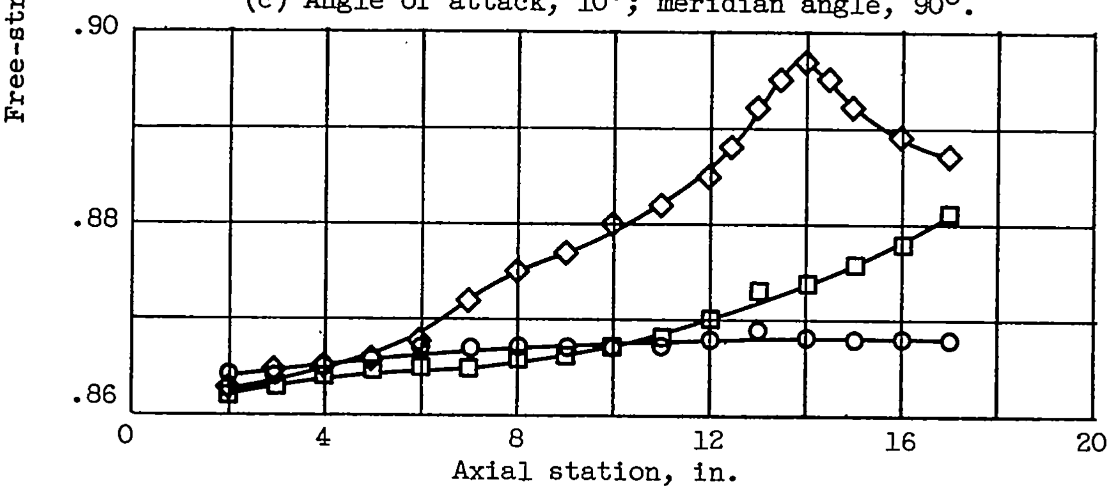


(b) Angle of attack, 10°; meridian angle, 180°.

Figure 2. - Effect of Reynolds number on free-stream recovery-factor distribution.

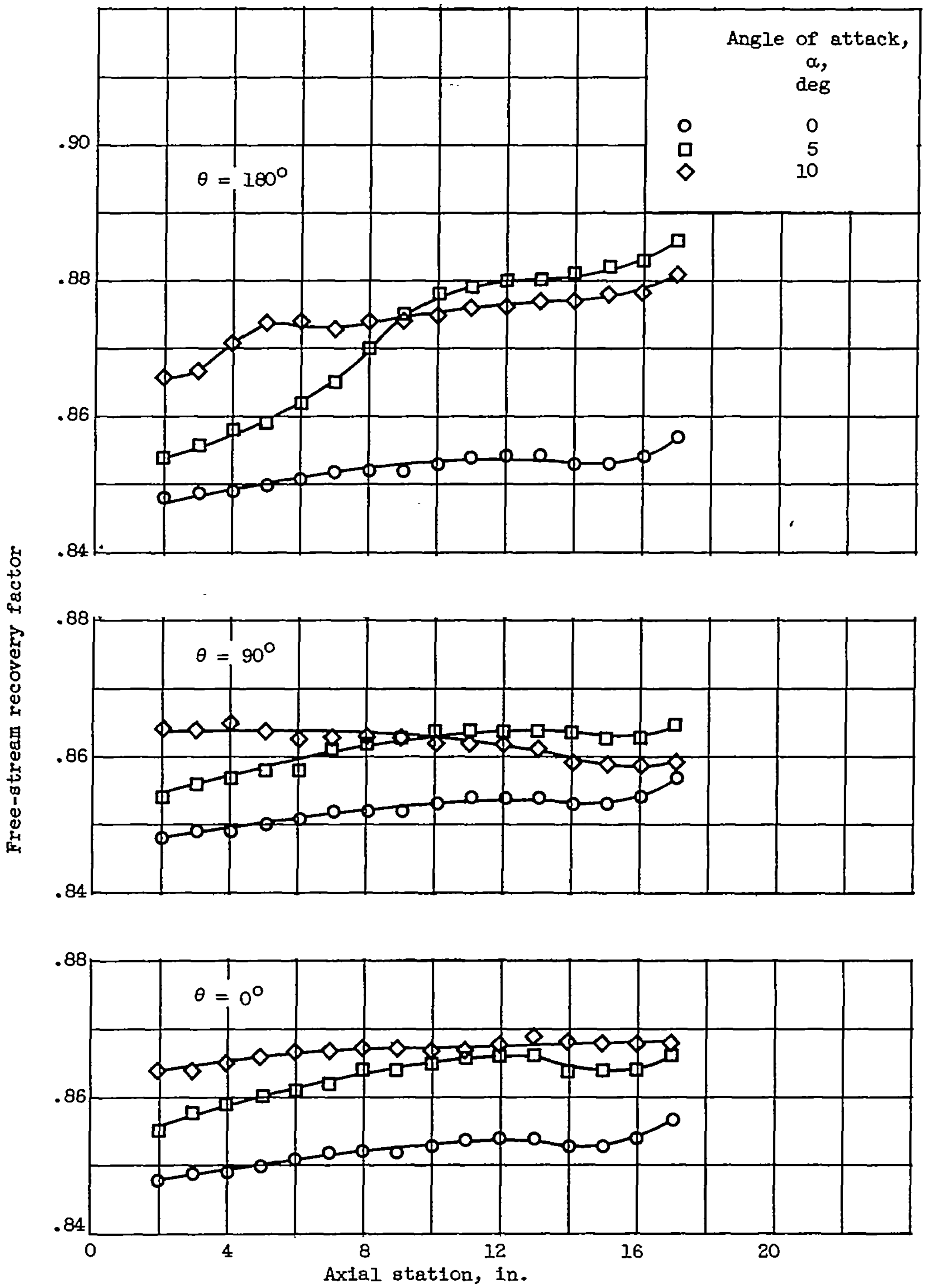


(c) Angle of attack, 10°; meridian angle, 90°.



(d) Angle of attack, 10°; meridian angle, zero.

Figure 2. - Concluded. Effect of Reynolds number on free-stream recovery-factor distribution.



(a) Reynolds number per foot, 1.5×10⁶.

Figure 3. - Effect of angle of attack on free-stream recovery-factor distribution.

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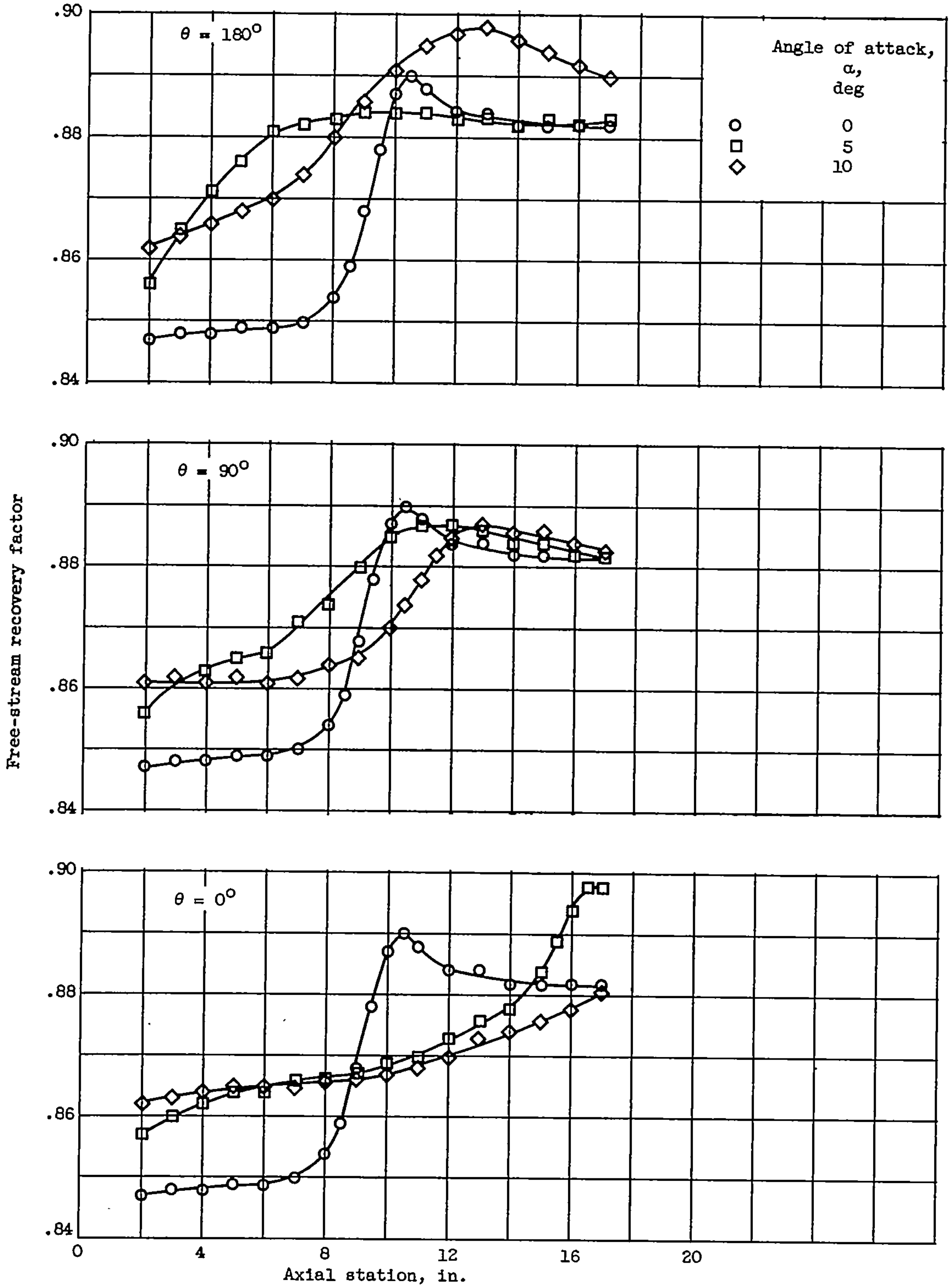
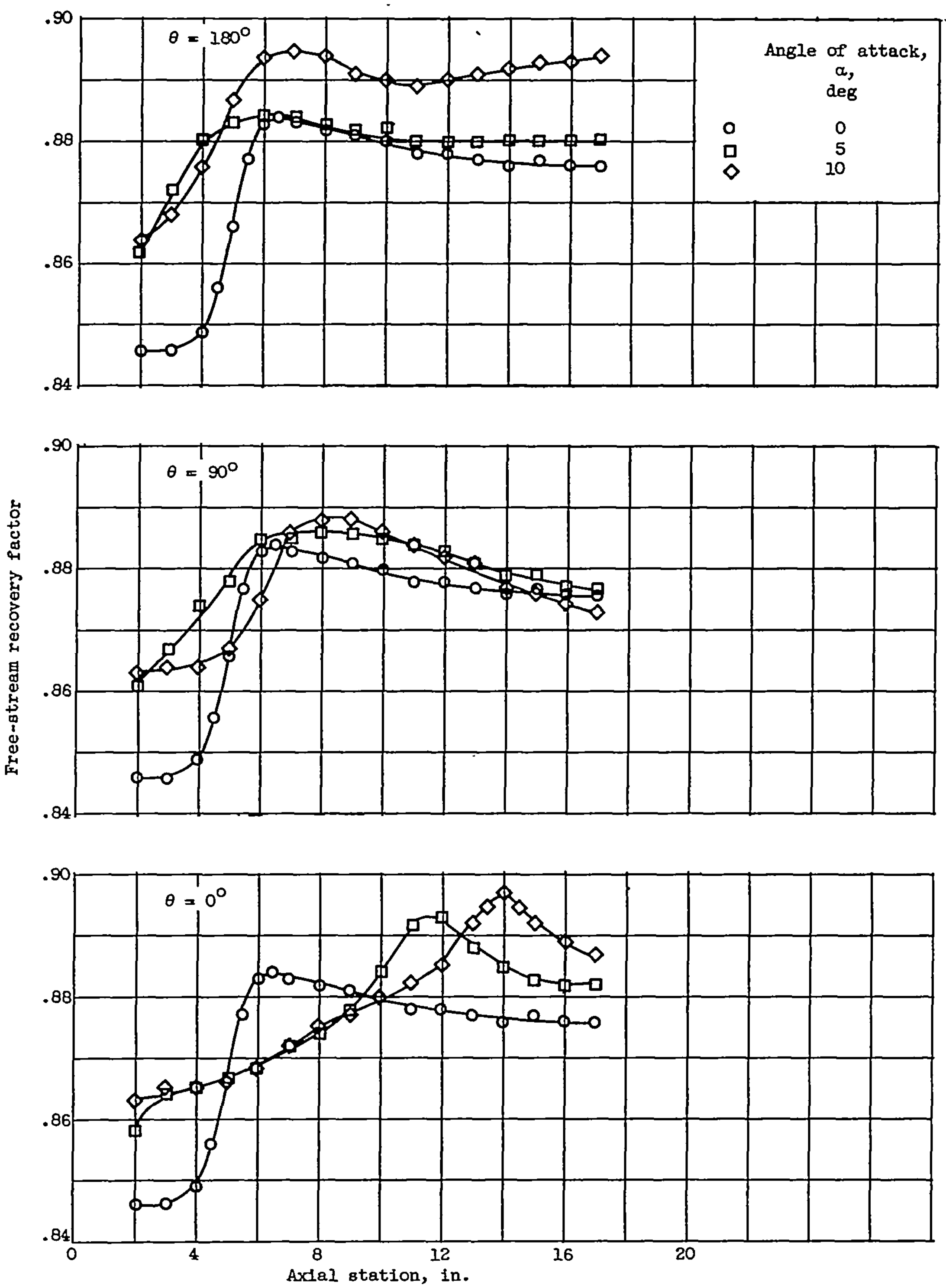


(b) Reynolds number per foot, 4.7×10^6.

Figure 3. - Continued. Effect of angle of attack on free-stream recovery-factor distribution.



(c) Reynolds number per foot, 8×10^6.

Figure 3. - Concluded. Effect of angle of attack on free-stream recovery-factor distribution.

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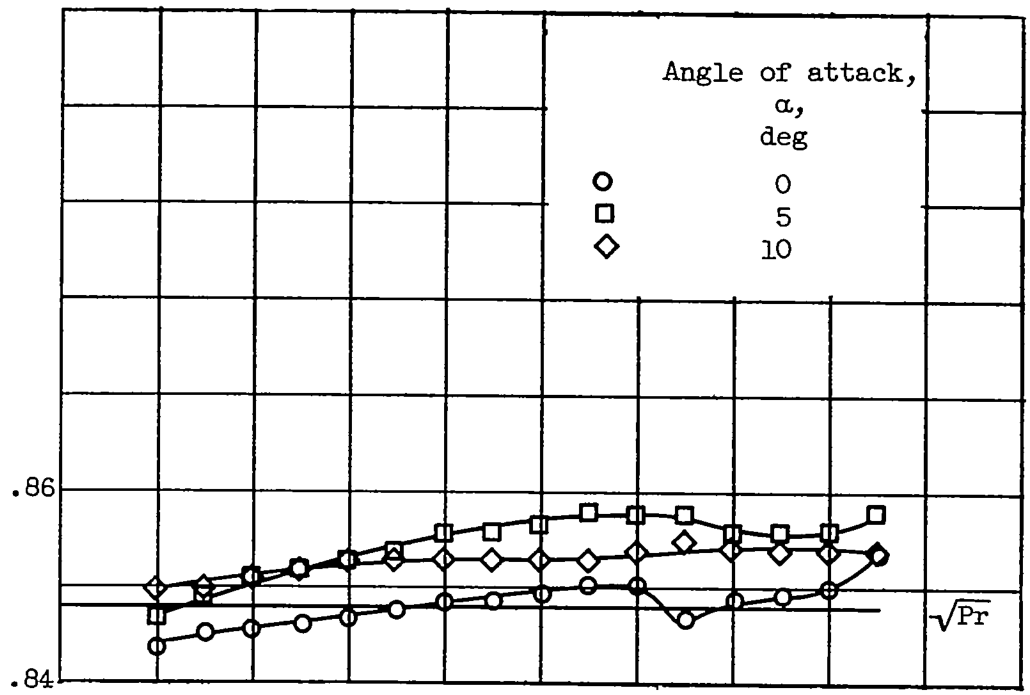
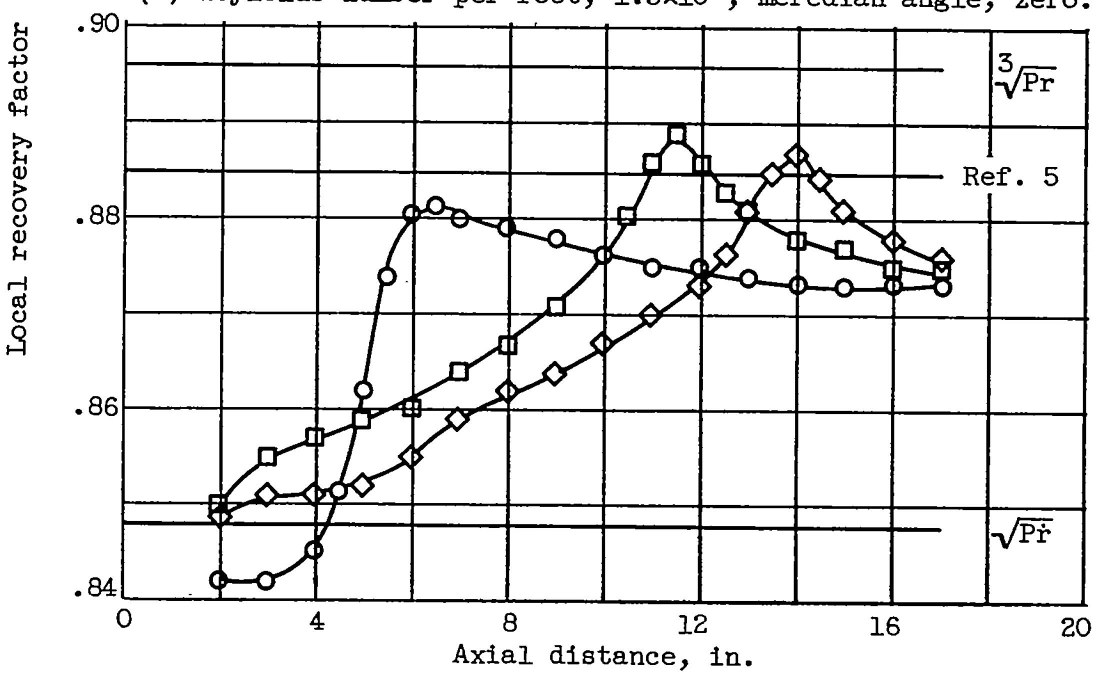


(a) Reynolds number per foot, 1.5×10[6]; meredian angle, zero.



(b) Reynolds number per foot, 8×10[6]; meridian angle, zero.

Figure 4. - Recovery-factor distribution based on local theoretical Mach number.

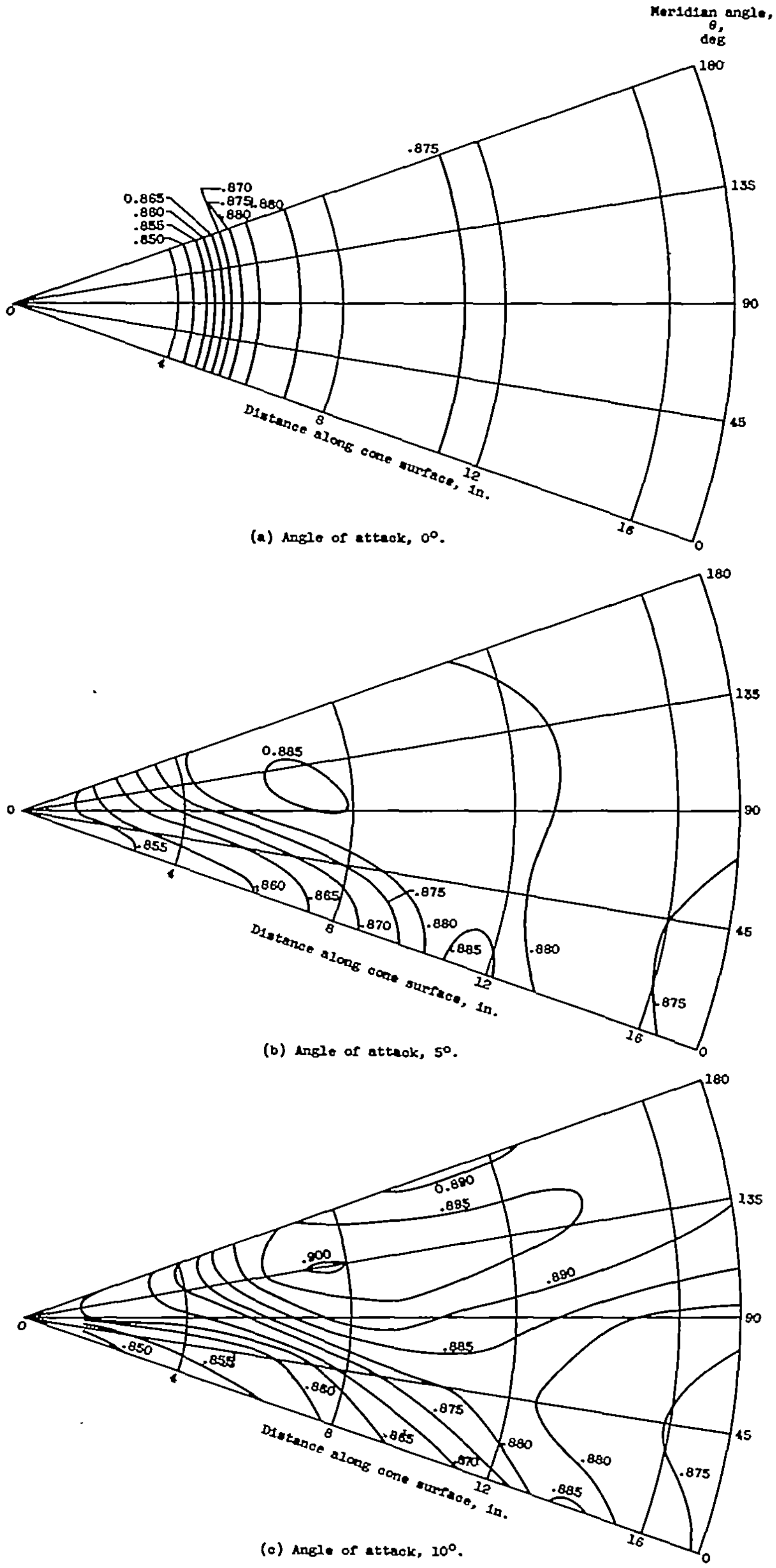


Figure 5. - Free-stream recovery-factor contours; Reynolds number per foot, 8×10^6.

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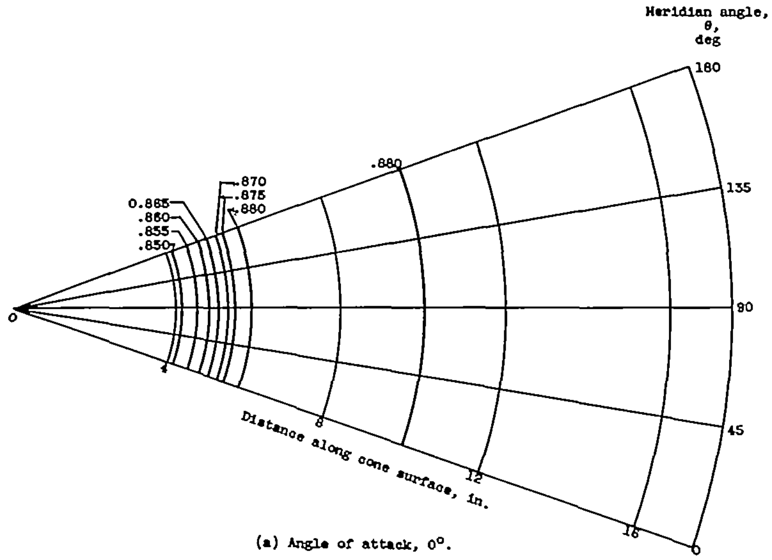
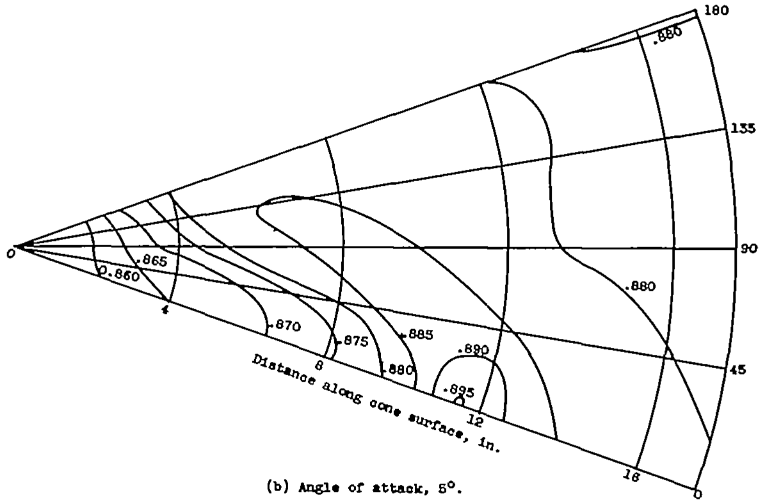
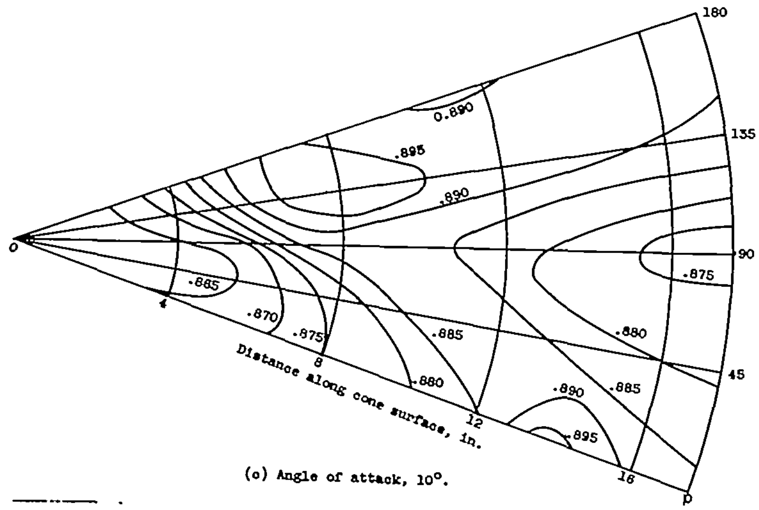


(a) Angle of attack, 0°.



(b) Angle of attack, 5°.



(c) Angle of attack, 10°.

Figure 6. - Local-recovery-factor contours; Reynolds number per foot, 8×10^6.

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